Assessment of the Danish High Speed Deflectograph in France

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ABSTRACT: The High Speed Deflectograph (HSD), developed by the Danish Road Institute and Greenwood Engineering A/S, measures the speed of vertical deformation of the road surface under the action of a load by means of two laser sensors with Doppler effect. During autumn 2003, LCPC assessed this prototype in the north of France. To make the tests, three different routes (motorway, trunk road and secondary road) were selected. Each route comprised a 2 km test section on which the HSD carried out several runs. The FWD took measurements on the same sections. Measurements of the HSD comprise the slope of the tangent to the basin of deflection at the point of measurement of the Doppler sensor. This parameter relates to the bearing capacity of the roadway and is the object of the analysis, which comprises the calculation of the repeatability on measurements of the test sections and the comparison of the values of the HSD with those of the FWD. Comparisons with the Flash deflectograph were also made. The conclusions of the study underline that HSD measurements are repeatable and could detect clear differences in levels of deflection. Following this assessment, a new HSD prototype has been designed.

KEY WORDS: Bearing capacity, deflection measurements, road pavement, high speed, velocimeter.

1 INTRODUCTION

Bearing capacity of road pavements is essential for optimum planning of road maintenance and rehabilitation. Current methods employ slow moving or static measurement techniques to evaluate the structural condition. These methods are expensive to operate and often hazardous to operators and road users.

In recent years, a number of countries have developed prototypes to measure bearing capacity at traffic speed. The Danish Road Institute (DRI) and the Greenwood Engineering (GE) have developed such a device called the High Speed Deflectograph (HSD) (Hildebrand et al., 2002, Rasmussen et al., 2002). It is based on an original idea that consists of measuring the deflection velocity of the pavement surface using laser Doppler sensors.

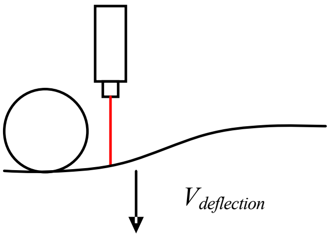
In the framework of the European FORMAT project high speed monitoring equipment currently available as prototypes were assessed. The Laboratoire Central des Ponts et

Chaussées (LCPC), DRI and GE performed the assessment of the HSD prototype in the north of France in October 2003. The paper reports this assessment.

2 HSD PRESENTATION

The High Speed Deflectograph concept is based on the measurement of the deflection velocity rather than the absolute deflection of the road surface. The concept is well-suited for testing at high driving speeds as the deflection velocity increases with increasing driving speed, although not linearly.

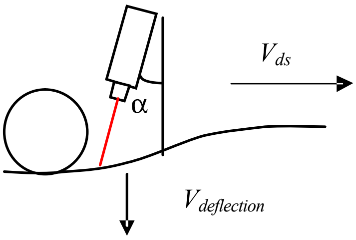
A laser Doppler sensor is mounted in front of one wheel on a heavy loaded vehicle. The laser beam emitted from the Doppler sensor strikes the road surface and the sensor measures the velocity in the direction of the laser beam. The loading of the road surface by the wheel yields a deformation of the road surface and the Doppler sensor registers the velocity of this deformation.



$$V_{measured} = V_{deflection}$$

Figure 1: Velocity deflection measured with a Doppler sensor.

Because the Doppler sensor is not positioned exactly perpendicular to the road surface the laser beam does not strike the road surface at an angle α of incident of exactly 0 degrees. Hence, the Doppler sensor registers - in addition to the desired deflection velocity - also a component of the driving speed V_{ds}:



$$V_{measured} = V_{deflection} + V_{ds} \sin \alpha$$

Figure 2: Velocity relationship for one Doppler sensor.

To correct for this, the angle of incident of the laser beam on the road surface needs to be measured accurately together with the driving speed.

The angle is measured by means of a second laser Doppler sensor placed outside the deflection bowl. The sensors are mounted on a stiff beam to ensure that the relative angle between the sensors remains fixed.

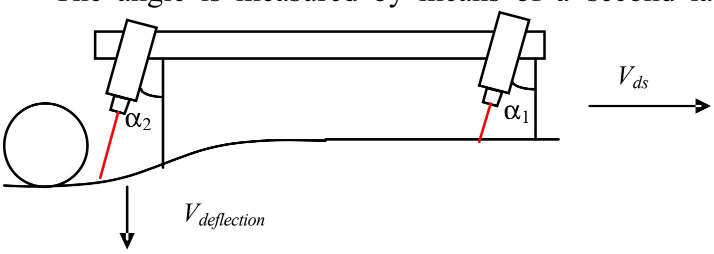


Figure 3: Principle of velocity measurement using 2 Doppler sensors.

If α_1 and α_2 are the angles of incident of the reference sensor and the deflection sensor respectively and V_{m1} and V_{m2} are the values measured by the sensors, then

$$V_{m1} = V_{ds} \sin \alpha_1$$
$$V_{m2} = V_{deflection} + V_{ds} \sin \alpha_2$$

In the case where $\alpha_1=\alpha_2=a$ the deflection velocity can be found directly by subtracting the velocity measured by the reference sensor from the velocity measured by the deflection sensor and

$$V_d = V_{m1} - V_{m2}$$

Obtaining the same angle of incident for both sensors is unfortunately not practical. If $a_c=a_2-a_1$ then

$$V_{deflection} = V_{m2} - V_{ds}\sin\{a_c + \arcsin(\frac{V_{m1}}{V_{ds}})\}$$

The angle a_c is determined during a calibration procedure and the driving speed V_{ds} is measured using an odometer.

As the Doppler sensors register the relative velocity between the sensors and the road surface it is necessary to adjust the data for the movement of the sensors. The movements are determined using an inertial unit composed of three accelerometers and three gyros.

Figure 4 shows a measuring beam with two Doppler sensors similar to the layout of the HSD prototype. The Doppler sensor positioned inside the deflection bowl provides information about the deflection velocity approximately 300 mm in front of the centre of the load. For production versions of the equipment it is recommended that more sensors are added inside the deflection bowl to facilitate the collection of information from several positions.

Figure 4: The towing truck, the semi trailer and the measuring sensors mounted on a stiff beam in front of the right hand side twin wheel. The stiff beam is servo controlled to keep the sensors focused.

3 PRINCIPLE OF THE ASSESSMENT

The testing program was suggested by the LCPC and accepted by the DRI and GE. The LCPC wished to assess the prototype in normal conditions of measurement. The objectives of the HSD assessment were to specify the performance of the prototype in two different situations:

- Long routes which would allow a survey of the structural performance;
- Short sections, about 2 km long, where detailed assessment of bearing capacity was expected.

To carry out the tests, three different routes (motorway, trunk road and secondary road) were selected. Their length varied between 8 to 15 km and they represented various types of pavements that one can find on the European road networks. Deflection measurements at 10 meter intervals with the French Flash Deflectograph were used as reference to assess the HSD. Other information was also available from databases or from specific measurements (GPR, transverse and longitudinal profiles, video).

On each road, a homogeneous section was identified as the short section for the repeatability tests. FWD measurements were made at 10 meter intervals on the short sections to complete the available information.

The HSD was supposed to carry out:

- 2 or 3 runs on each route in each direction;
- 3 runs at reduced speed and 5 to 10 runs at normal speed on the short sections;

4 TESTS PERFORMED

The tests were conducted in northern France near the cities Dunkerque and Cambrai durig the period from 22 September until the 1st October 2003. After calibration of the equipment on 22nd September a technical problem happened with the conditioning velocimeter system. The problem was due to a failure in the electronic data acquisition in one of the two laser Doppler systems. After the system was been repaired, the testing program was adapted and it was suggested to continue the assessment the following week. Table 1 summarizes the testing program, which was actually carried out:

Table 1: Tests conducted with the HSD on the different test sections.

Date	Type Road	Type of test section	Length (km)	Number of run(s)	Comments
25/09/03	Motorway	Short section	2	8	Speed: 60-70 km/h
26/09/03	Motorway	Route	6	1	Speed: 70 km/h
30/09/03	Trunk road	Short section	2	9	3 runs at 40 km/h, 6 runs at 70 km/h
30/09/03	Secondary road	Short section	2	6	3 runs at 40 km/h, 3 runs at 50 km/h
01/10/03	Secondary road	Route	8	1	Windy and wet weather, 1 run at 40 km/h

On the 1st October some rain fell. As the weather forecast was not optimistic, and measurements had been made on each type of roads, we decided to stop the trials.

5 RESULTS FROM FIELD TRIALS

DRI and GE processed and delivered data which included: Time, location, driving speed, data rate, deflection velocity, slope of the deflection bowl. Each data was delivered at an interval of a millisecond. LCPC adjusted the measurement locations using specific road marker to synchronize the different runs on the same road. HSD results were aggregated as an average mean value every 10 or 50 meters to compare it to the FWD or Flash Deflectograph measurements. In the following we just present 10 meter averages of the parameter called slope of deflection bowl.

Figure 5 compares slope HSD measurements and deflection measurements from the Flash Deflectograph on a route with a flexible pavement structure. First of all, one must remember that small rain showers fell during these trials. However, this route presents different deflection levels which was the reason why LCPC originally selected it. The figure shows that the results from the two devices are very similar even if the parameters are not same. We can easily identify a rigid section near the 23000 m abscissa.

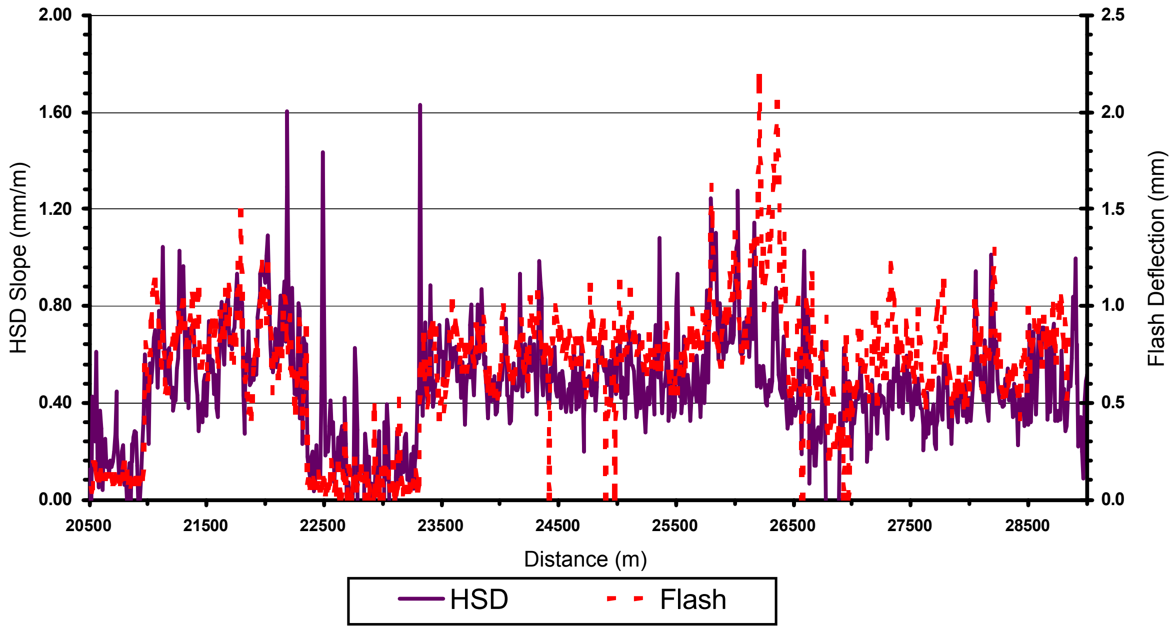


Figure 5: Comparison between HSD slope measurements and Flash deflection measurements on the flexible route.

Figure 6 compares the results on the motorway. Six runs correspond to the trials on the 2 km short section and one run corresponds to the trial on the 6 km route. On this rigid road the deflection from FWD is about 100 µm. One can note:

- The results from short runs are similar;
- A systematic difference exists between the results from the long run and the short runs.
- There are some points with a high level of deflection/HSD slope.

To explain the difference, one should know that the measurements for the short runs were done on the 25th September in the evening (8 to 11 pm) while the long run was done in the morning of the 26th. Moreover, the calibration process was done just before this last run. Nobody knows if the differences come from the pavement or from the HSD?
Using the video, we can explain the points with high level of response in the measurements (marked with P1, P2 and P3 in Figure 6). They are located at bridge expansion joint places.

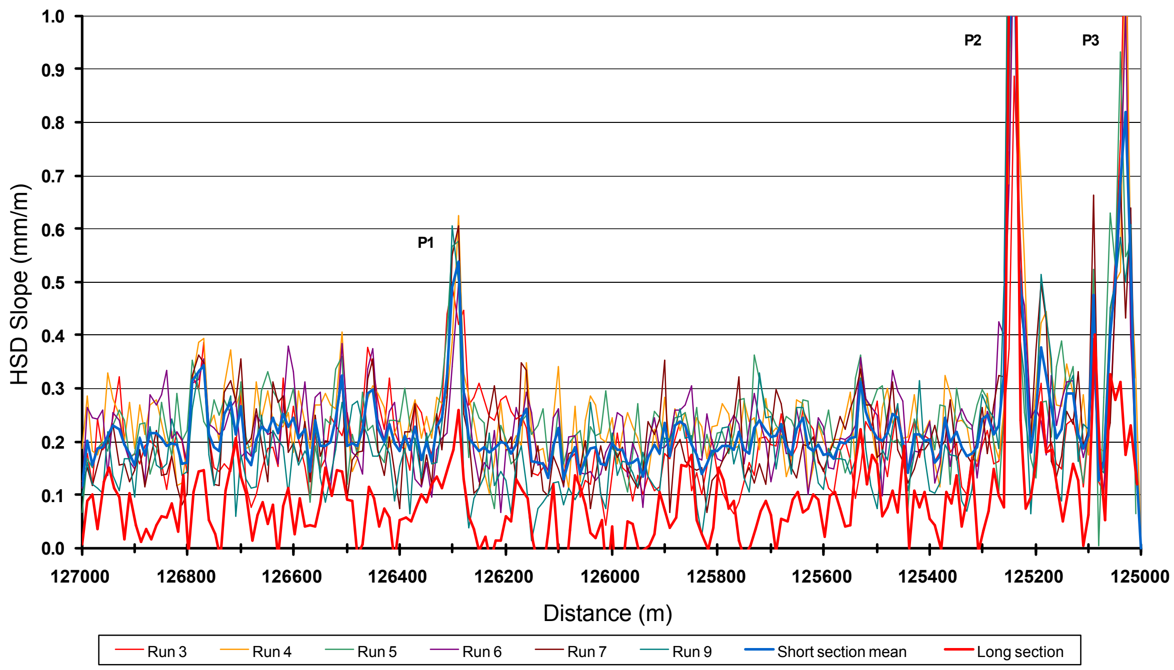


Figure 6: Comparison between HSD slope measurements on the motorway; short section runs and long section run.

Figure 7 shows the six runs of the HSD on the trunk road at 70 km/h. Mean value and standard deviation is presented on the graph. The standard deviation is much less than the mean value, which shows a good repeatability of the device.

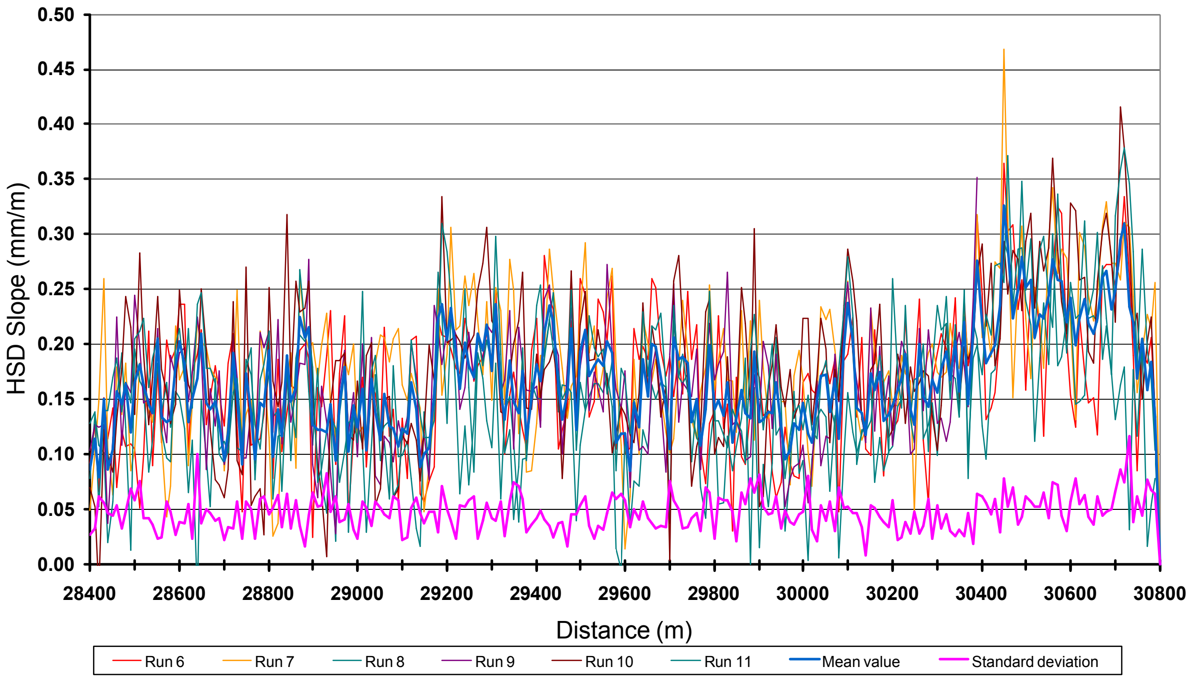


Figure 7: Comparison between HSD slope measurements on the trunk road short section ; individual runs, mean value and standard deviation.

Figure 8 compares deflections from the Flash Deflectograph and the FWD to the slope measured by the HSD. The level of the deflection measurements are similar on the two rigid sections. On the flexible section, the Flash Deflectograph measures higher deflection than the FWD.

Compared to the deflection measurements, the HSD slope measurements allows us to define the limits of the different sections. One can see that the classification according to the measurements level is different, but we have to keep in mind that the measured parameter is different.

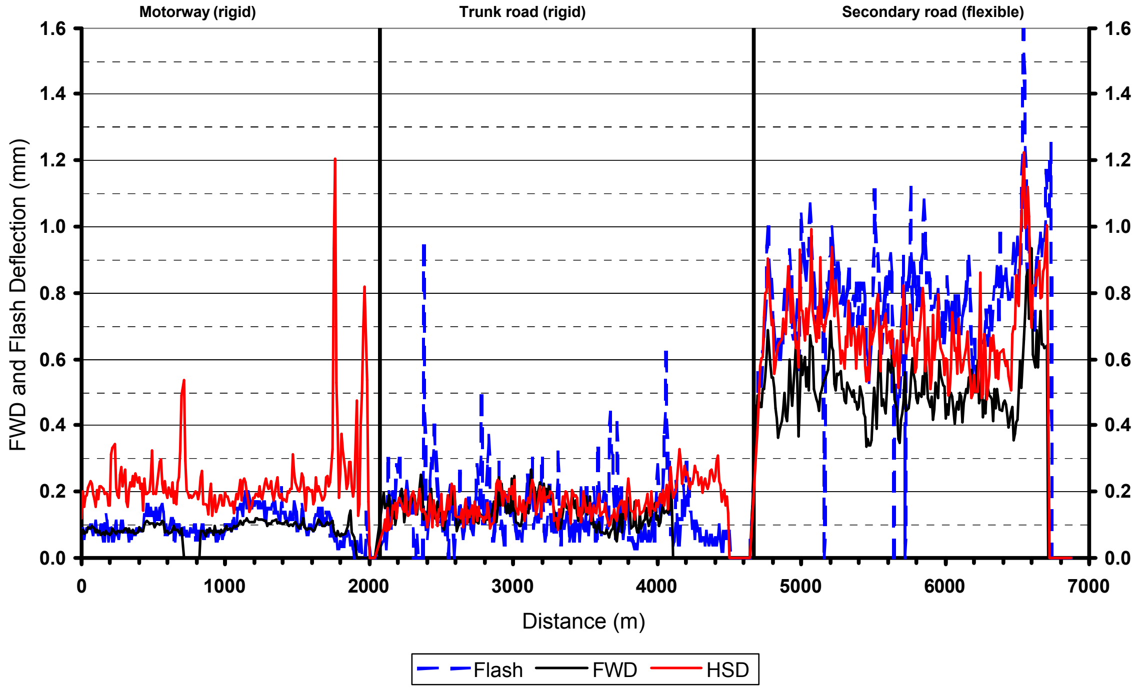


Figure 8: Comparison between HSD slope measurements, FWD and Flash deflection measurements on the three short sections.

Figure 9 compares the HSD slope measurements to the FWD deflection measurements. A linear regression was successfully calculated with a regression coefficient equal to 0.86. On this graph, one can easily distinguish the three types of roads. We can see that the set of measurements on the motorway is above the regression line while the one of the trunk road is under the line. So, converting HSD slope measurements to absolute deflection using this linear regression is not recommended.

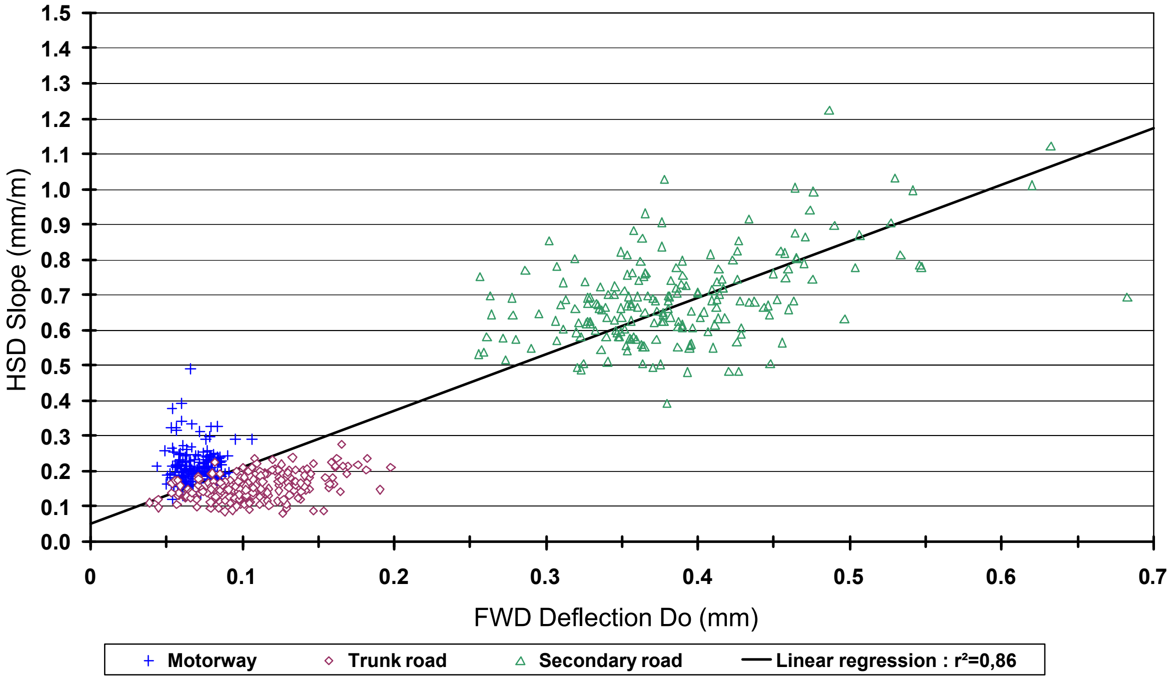


Figure 9: Comparison between HSD slope measurements and FWD deflection measurements Do.

6 CONCLUSIONS AND PERSPECTIVES

The HSD is a research prototype, which was designed to confirm a specific concept. The assessment confirms the concept of the HSD. The estimated slope is sensitive to the bearing capacity. The assessment showed also some elements of the performance of the future device.

About the HSD working aspect, the following points are to be underlined:

- The velocimeter sensors seem to be sensible to temperature and wind;
- The initial warming-up time of the sensors before measurement is a major constraint;
- The calibration phase takes a long time and is delicate. It may take up to a half-day to determine the relative optimal position of a sensor compared to the other and the angle of the beam which supports them compared to the road surface. Moreover, it infers to take measurements on a rigid pavement.
- The HSD is able to run up to 70 km/h during measurement (It does not disturb the traffic);
- A real time velocimeter measurements quality indicator is available (Data rate);
- The data rate is very sensitive to the atmospheric conditions such as temperature and, like any laser system, to rain. It takes into account the angle of incidence of the light ray of the Doppler sensors onto the road surface and the driving speed, hysteresis effects, the laser focusing of the sensors adjusting the position of the measurement beam according to the road surface, and the temperature.

About the metrological performances, the assessment showed that:

- The HSD slope measurements are repeatable;
- The HSD slope measurements are sensible to measurement conditions (temperature, wind);
- The HSD slope measurements are comparable with the FWD and the Flash measurements. However, HSD measurements should not be converted into deflection measurements using the linear regression found;
- The HSD is able to detect clear differences in bearing capacity levels of a roadway.

In March 2005 an operational device is under development which takes into account the experience from this assessment. The new HSD will include:

- Four Doppler sensors instead of two
- Climate controlled environment for the equipment
- Improved design of the stiff beam with low susceptibility to changes in temperature and narrowing of the range of velocities measured
- Suspension system for protecting the electronics against shock
- New gyros with increased accuracy
- Electro-hydraulic system for shorter calibration procedure
- Special hub between the twin wheels to allow measurements to take place close to the center of the load (100 mm)

To confirm and refine the results obtained during this evaluation, it would be necessary to schedule new trials with the modified HSD.

The current results are promising; however the interpretation of measurements remains to be refined. Two ways could be considered:

- The integration of a set of measurements obtained with several Doppler sensors to calculate a deflection basin, as the designers of the HSD propose it, to process the measurements with existing methods like the Surface Curvatur Index (SCI);
- The direct interpretation of the slope of the tangent, as the technical network of the LCPC does for the measurement of the radius of curvature with the inclinometer.

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